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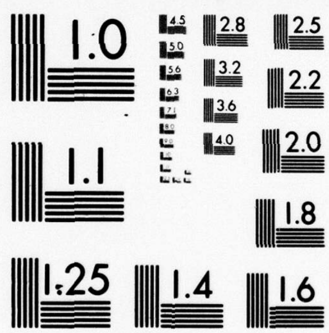

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ANALYTIC AND SIMULATION RESULTS FOR CSMA CONTENTION PROTOCOLS

BY C.E. LABARRE

MAY 1979

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RICHARD V. GOULD, L/Col, USAF
Asst Director of Engineering
Deputy for E-4

JOHN C. BREEDING, Major, USAF
Chief, C^3 Division
Deputy for E-4

DONALD L. SCOTT, Col., USAF
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The behavior and comparative performance of the Listen-While-Talk (LWT) and Listen-Before-Talk (LBT) CSMA contention protocols are examined using analytic and simulation techniques. The equilibrium throughput and delay equations for the non-persistent LBT and LWT protocols are derived. Simulation results are

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20. Abstract (continued)

provided for the 1-persistent LWT and LBT protocols as implemented on the MITRE coaxial cable system. The throughput and delay performance of the LWT protocol is demonstrated to be superior to that of other contention protocols for use in local networks. Dynamic control procedures, similar to those used in other contention systems, are applicable to LWT CSMA protocols.

ACKNOWLEDGMENT

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1.0 INTRODUCTION

Resource sharing, the sharing of a limited amount of resources among a multitude of users, has been the driving force behind the creation of multi-access computer systems and computer networks. A variety of techniques have been developed to share computer resources, for example: multiprogramming, time-sharing and network control procedures. Emphasis is currently being placed on efficient sharing of the channels used for communication among the terminals and computers in these systems. The demands placed on the channels are usually of a "bursty" nature, that is, they possess a high ratio of peak to average traffic rate. Communication techniques have been invented which utilize the statistical nature of the demands on the channels to more efficiently share their capacity among a large community of users. One such technique is packet broadcasting [1] on a single high capacity channel that is shared by all users, often referred to as bussing.

A broadcast channel may be shared on an assigned basis in which users take turns in transmitting, or on a contention basis where users contend for access to the channel. Contention techniques allow users to contend or collide when transmitting and require users to sense these collisions and retransmit after a random delay. The contention techniques are split into ALOHA [1] and Carrier-Sense-Multiple-Access (CSMA) protocols [2]. ALOHA users transmit any time they desire; CSMA users transmit only when they sense the channel is free. CSMA protocols may be further partitioned into Listen-Before-Talk (LBT) and Listen-While-Talk (LWT) protocols. LBT users do not listen to their own transmissions; LWT users listen while they are transmitting. Detailed analysis of the LBT CSMA protocols are given in References [2-3]. An analysis of the LWT protocol is provided in this report.

One purpose of this study was to estimate the magnitude of the channel throughput and delay advantage offered by the LWT protocol over the LBT protocol. Another objective was to determine if the dynamic control procedures used to control channel equilibrium for the LBT CSMA [4] and ALOHA [5] protocols are applicable to the LWT CSMA protcol.

Several variations of the CSMA protocol were investigated. The throughput and delay performance of the LWT and LBT protocols were compared using analytical techniques (Sections 3-5) and computer simulations of a CSMA coaxial cable based system implemented at MITRE (Section 6). The causes of channel instability were investigated using simulation techniques (Section 6).

2.0 THE CSMA CONTENTION PROTOCOL

A CSMA contention protocol is a technique for sharing the broadcast channel by independent users* who attempt to avoid collisions by listening for (i.e., sensing) the presence of other transmissions on the channel. Users having a packet to transmit will defer if they sense the channel is busy. Collisions result when two or more users sense the channel is free and attempt to transmit. The "vulnerable period", when two or more users may attempt to transmit without realizing each other's presence on the channel, is the propagation delay between the contending users. Users involved in a collision will independently reschedule their packets for retransmission after a random delay.

CSMA protocols are divided into two general categories: Listen-Before-Talk (LBT) and Listen-While-Talk (LWT).

a. Users operating in an LBT mode do not listen to their own transmissions. Collisions are detected after the total packet has been transmitted and a positive acknowledgement has not been received within a predetermined interval of time. Collisions tie up the channel for the duration of the overlapping packets plus propagation delays.

b. Users operating in the LWT mode listen to their own transmissions and cease transmission upon detecting the presence of others on the channel. All collisions are detected

---

*Users are devices which interface the network components, e.g., computers and terminals, to the broadcast channels.

within the maximum propagation delay between users on the channel. Collisions tie up the channel for the duration of the overlapping propagation delays.

Each of the above CSMA protocols are further differentiated according to the action that a user takes after sensing a busy channel. A user sensing the channel busy may reschedule the next time to sense the channel after some random delay (non-persistent CSMA), or may persist in sensing the channel and transmit with probability 1.0 when the channel becomes idle (1-persistent CSMA), or may persist in listening until the channel becomes idle and delay a random time before transmitting if the channel is still idle (p-persistent CSMA). Each of these protocols has been analyzed by F. Tobagi [2] for LBT CSMA.

3.0 ASSUMPTIONS OF THE ANALYTIC MODEL

The assumptions made about the model are similar to those stated by F. Tobagi and L. Kleinrock [1, 2] to facilitate comparison with their results for the LBT CSMA protocols. The assumptions are stated below.

A1. All packets are of constant length.

M. Ferguson [6] has shown for a random access channel that a variable packet size is always inferior, in terms of channel efficiency, to a fixed packet size.

A2. The channel is noise-free.

A3. The overlapping in transmission time of any fraction of two packets results in destructive interference and both packets must be retransmitted.

A4. No packets collect at each individual use, i.e., a user transmits the previous packet before the next packet arrives.*

Assumptions A4 and A5 prohibit multipacket messages and dictate that the time between packet arrivals from a user must be greater than a packet transmission time. Assumption A5 may be valid for most terminal users on

*The gross arrival rate to the system during an interval of time T is therefore $\lambda(N-m)$ instead of λN where λ = arrival rate to each user, N = number of users, m = number of users having a packet to transmit during the interval T.

the channel, but processors connected to the channel may need to queue messages for transmission to terminal users. The assumption of Poisson distributed channel traffic is weakened for higher values of G. Stability analysis and simulation results by Tobagi [2] for LBT CSMA indicate that the infinite population assumption results closely approximate the results for a finite population of 50 to 200 users.

A5. G, the offered channel traffic, is Poisson distributed. The offered channel traffic includes all new arrivals to the system plus all arrivals due to rescheduling as a result of collisions and deferrals. Traffic is generated from an infinite population of users. The interarrival time distribution is exponential with mean 1/G.

A6. The average retransmission delay, $\bar{X}$, is large compared to the packet transmission time T.

Analytic and simulation results by Tobagi [2] for LBT CSMA, as well as LWT CSMA simulations from this study, indicate that for mean retransmission delays, $\bar{X} \gtrsim T$, the system approaches the asymptotic results for $\bar{X} \gg T$.

A7. A user may be transmitting a packet or receiving a packet from another user (but not both simultaneously), with a negligible delay in switching from one mode to the other. However, LWT users can simultaneously transmit and receive their own packet.

A8. The time to detect the presence of a transmission on the channel is zero.

A9. All transmissions are heard by every user connected to the channel.

A10. The propagation delay is small compared to the packet transmission time and is identical for all source destination pairs.

Using the maximum possible propagation delay for all users yields lower bounds on system performance. The average ratio (a) of propagation delay to packet duration is typically between .001 and .1 for local packet ratio and coaxial cable based networks.

A11. The channel for acknowledgement is separate from the data transmission channel.

Acknowledgement traffic does not use any of the capacity of the data channel and thus does not affect the channel throughput. However, delays due to acknowledgements are a significant part of system response time.

The above assumptions do not reflect accurately the characteristics of any implemented system. However, they do provide a common basis for an analytical comparison of several contention protocols [1-4]. The relative performances of the LBT CSMA [2-4], ALOHA [5] and LWT CSMA (Section 6.0) protocols have been verified through simulation studies with many of the assumptions relaxed to more closely model actual system implementations.

4.0 THROUGHPUT ANALYSIS

The equilibrium throughput equations for non-persistent LWT CSMA and non-persistent LBT CSMA are derived in this section. The throughput equation for LBT CSMA is found to differ from the equation derived by F. Tobagi[2]. A comparison is made of the throughput for the LWT CSMA, LBT CSMA and ALOHA [1,5] protocols.

4.1 Throughput Analysis for Non-Persistent LWT (N-LWT) CSMA Protocol

The equilibrium throughput equation expressed in terms of S (the average throughput), a (the ratio of propagation delay to packet transmission time) and G (the offered channel traffic) is:

$$S_{N\text{-}LWT} = \frac{Ge^{-aG}}{G(e^{-aG}+a) + (1 + aG)\,(1-e^{-aG})^{2} + 1} \qquad (1)$$

The derivation of (1) is based on the cyclic nature of the busy and idle time intervals on the channel. A busy interval (B) occurs when a signal is present on the channel. An idle interval (I) is the time between two busy intervals. A cycle consists of a busy interval followed by an idle interval. U is the portion of time during a cycle that the channel is used for a successful transmission. From renewal theory [2,7] the expected channel utilization, or throughput, can be expressed in terms of the mean values of the above quantities as

$$S = \frac{\bar{U}}{\bar{B} + \bar{I}} \qquad (2)$$

The quantities $\bar{B}$, $\bar{I}$ and $\bar{U}$ are defined more precisely with reference to Figure 1. All times are normalized to the duration of a packet transmission, $T = 1$. Let t be the time of arrival of a packet which senses the channel idle and hence, initiates a busy interval. Any other packet arriving between t and t+a will sense the channel idle, will transmit and cause a collision. The first packet will be successful if no other user transmits a packet during the propagation delay, a.

The case in which collisions occur will be analyzed first. Let t+z be the time when the second packet arrives during the interval (t, t+a). All users, except the first, have ceased transmitting by t+a since later users will have detected the presence of the first user on the channel at the end of the propagation delay. The first user will detect the collision at time t+z+a, i.e., a propagation delay after the second user begins transmitting. A propagation delay after the first user ceases transmitting the channel will be sensed idle. Any user sensing the bus between t+a and t+z+2a will find the channel busy and will reschedule its packet for transmission.

A user which successfully seizes the channel will transmit during the interval (t, t+1). All users will sense the channel idle a propagation delay after the transmission ends.

The probability of a successful transmission during a busy period is the probability that no other user transmits within a propagation delay, a, after the beginning of the transmission.

$\bar{U} = e^{-aG}$

$\bar{I}$ = average interarrival time = $1/G$

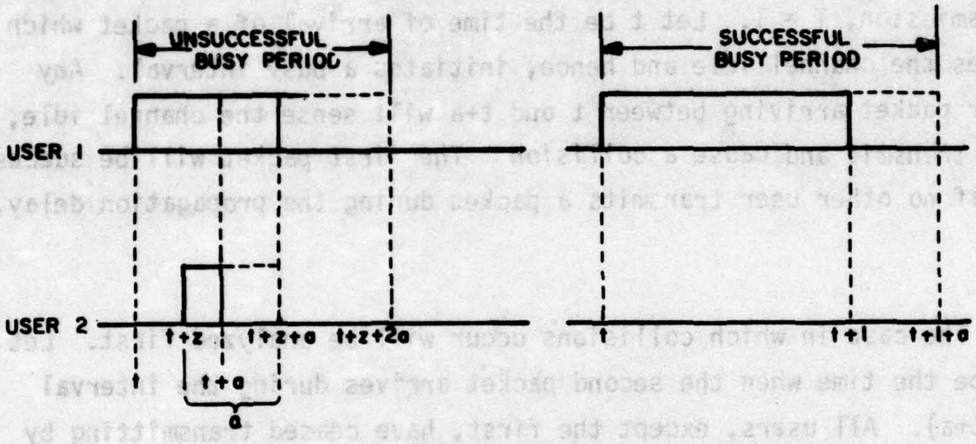

Figure 1 - LWT CSMA CHANNEL BUSY PERIODS

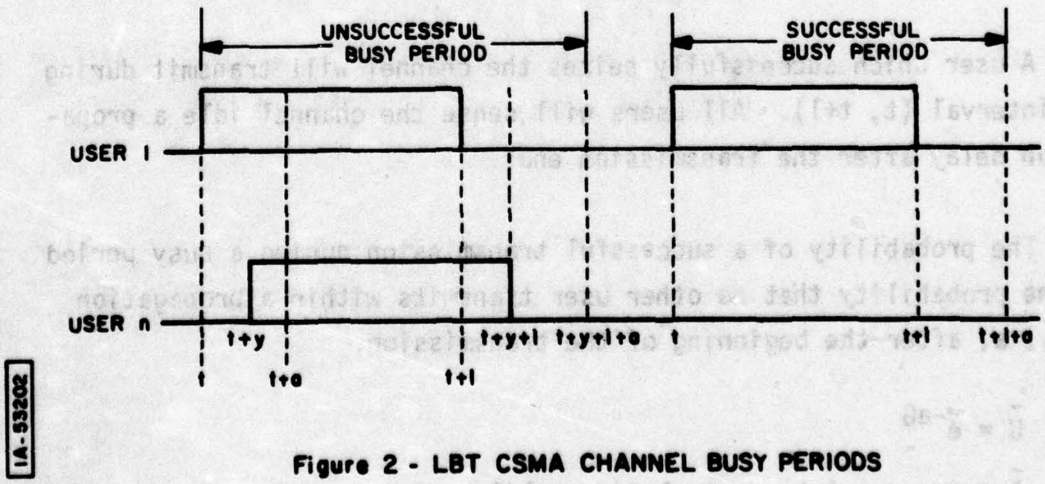

Figure 2 - LBT CSMA CHANNEL BUSY PERIODS

$$\bar{B} = P(\text{successful busy period})\,(1+a) + P(\text{unsuccessful busy period})\,(\bar{Z}+2a)$$

$$= e^{-aG}(1+a) + (1-e^{-aG})(\bar{Z}+2a)$$

$$= e^{-aG} + (1-e^{-aG})\bar{Z}+a(2-e^{-aG})$$

$\bar{Z}$, the expected value of Z, may be calculated from the distribution function of Z:

$$F_Z(z) \triangleq P[Z \le z] = 1-P[Z>z] = 1-P\begin{bmatrix}\text{no arrival in time}\\ \text{z and at least one}\\ \text{arrival in time a-z}\end{bmatrix} = 1-[e^{-zG}(1-e^{-(a-z)G})]$$

z is defined on the interval (o,a). Therefore $\bar{Z} = \int_0^a [1-F_Z(z)]dz$

$$= \frac{1}{G}(1-e^{-aG})-ae^{-aG}.$$

Substitution of the expressions for $\bar{U}$, $\bar{I}$, $\bar{B}$ and $\bar{Z}$ into the equation for S (2) yields the equilibrium throughput equation for the non-persistent LWT CSMA protocol (1).

Notice that if the probability of success (e^{-aG}) is unity and $\bar{I}$ = 1/G = 0, as would occur with perfect scheduling, $\bar{B}$ equals the duration of a successful packet transmission (1+a). The maximum throughput with perfect scheduling is $S_{N\text{-}LWT} = 1/(1+a)$.

4.2 Throughput Analysis for the Non-Persistent LBT (N-LBT) CSMA Protocol

The equilibrium throughput equation derived for the non-persistent LBT CSMA protocol differs from the equation derived by F. Tobagi [2].

Tobagi's equation $$S_{N-LBT} = \frac{Ge^{-aG}}{G(1+2a) + e^{-aG}} \qquad (3)$$

New equation $$S_{N-LBT} = \frac{Ge^{-aG}}{G(1+2a-ae^{-aG})-(1-e^{-aG})^2+1} \qquad (4)$$

The derivation of the throughput equation for the non-persistent LBT CSMA is similar to the derivation provided by Tobagi[2]. The essential difference between the non-persistent LBT and LWT protocols may be discerned by comparing the unsuccessful busy periods as illustrated in Figures 1 and 2. The expected duration of the LWT unsuccessful busy period is $\bar{Z}+2a$ where $\bar{Z}$ is the average time when the <u>second</u> packet to participate in the collision arrives. The expected duration of the LBT unsuccessful busy period is $1+\bar{Y}+a$* where $\bar{Y}$ is the average time when the <u>final</u> packet to participate in the collision arrives and the entire packet must be transmitted.

$\bar{Y}$, the expected time of arrival of the last packet to participate in a collision, may be calculated from the distribution function of Y:

$$F_Y(y) \triangleq P[Y \leq y] = P\begin{bmatrix}\text{no arrivals occur in} \\ \text{interval of length } a-y\end{bmatrix} = e^{-(a-y)G}$$

Y is defined in the interval (o,a). Therefore $\bar{Y} = \int_0^a [1-F_y(y)]dy$

$$= a-\frac{1}{G}(1-e^{-aG}).$$

---

*F. Tobagi assumed the duration of the busy period to be $1+\bar{Y}$. This assumption accounts for the differences between Tobagi's throughput equation (3) and the equation derived in this section (4). Evaluation of the equations (3,4) for values of a between .001 and .1 indicate less than a 2 percent difference in maximum throughput.

The time intervals $\bar{U}$, $\bar{I}$ and $\bar{B}$ are defined as in Section 3.1.

$\bar{U}$ = average portion of cycle channel is used for successful transmission $= e^{-aG}$

$\bar{I}$ = average duration of idle interval = 1/G

$\bar{B}$ = average duration of busy interval

$$= P[\text{successful transmission}](1+a)+P[\text{unsuccessful transmission}](1+\bar{Y}+a)$$

$$= e^{-aG}(1+a) + (1-e^{-aG})(1+\bar{Y}+a)$$

$$= 1 + (1-e^{-aG})\bar{Y}+a$$

Substitution of $\bar{U}$, $\bar{I}$, $\bar{B}$ and $\bar{Y}$ into the equation for S (1), yields the new equilibrium throughput equation for the non-persistent LBT CSMA protocol (4).

4.3 Equilibrium Throughput Behavior of LWT CSMA and LBT CSMA Protocols

Figure 3 illustrates the throughput versus offered traffic for the non-persistent LWT CSMA, non-persistent LBT CSMA, 1-persistent CSMA and pure ALOHA protocols for a=.01 and a=.05. The 1-persistent LBT CSMA and ALOHA curves were calculated using the equilibrium throughput equations developed by Tobagi[2]. The throughput equations enable us to determine analytically the maximum throughput of the channel under equilibrium conditions. However, stability analysis and simulation results [2-5] indicate that near the maximum values predicted by the throughput equations the equilibrium assumption is not valid for any of the contention protocols. When the input traffic approaches the maximum value predicted for channel throughput, the

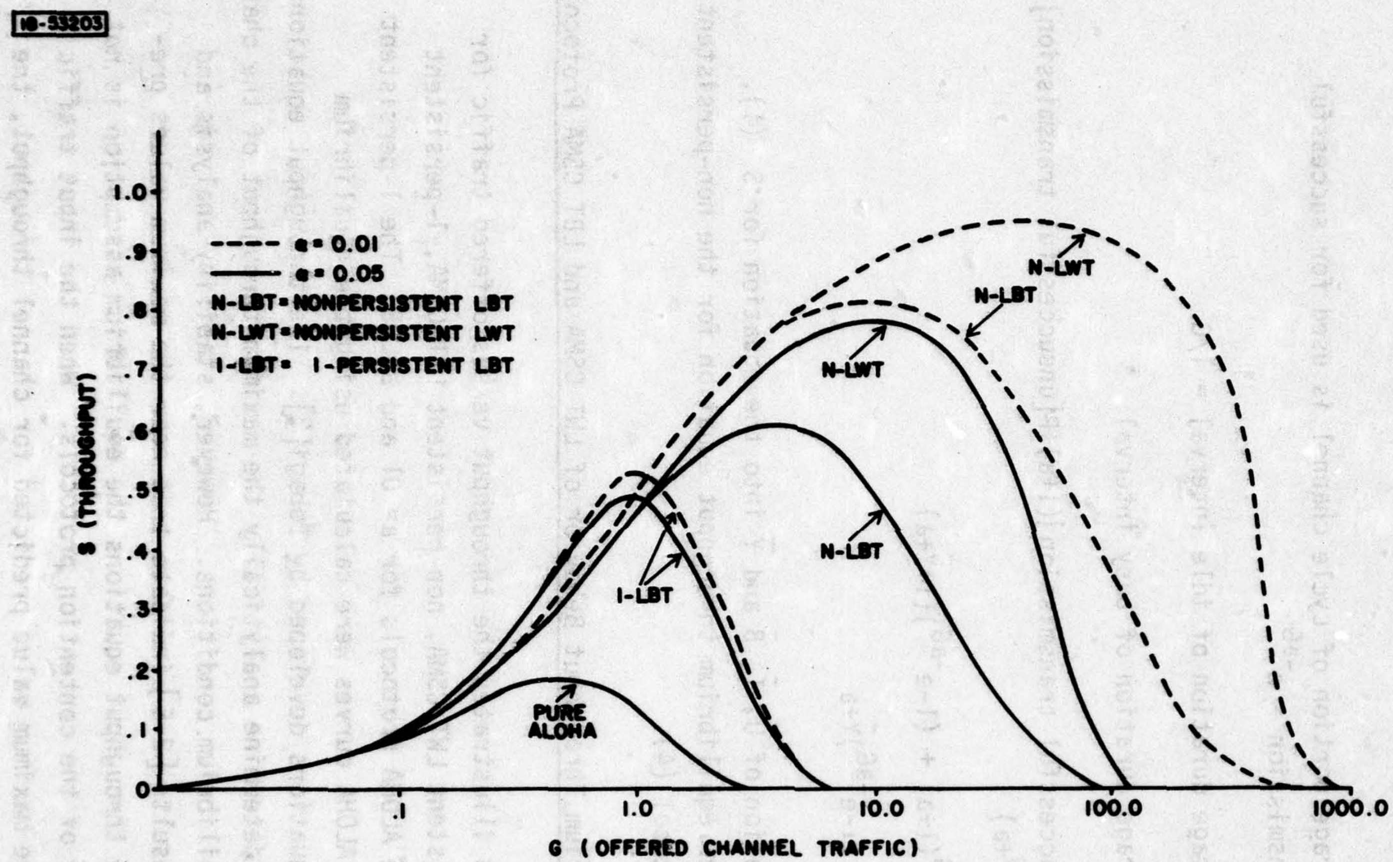

Figure 3 - ANALYTIC THROUGHPUT RESULTS

channel becomes saturated with collisions and throughput rapidly decreases to zero. This phenomenon is more fully discussed in Section 6.

The non-persistent LWT CSMA protocol offers an improvement in maximum throughput over the corresponding LBT CSMA protocol of approximately 10 to 30 percent for propagation delays between .01 and .05 packet durations. The proportion of the offered channel traffic due to collisions increases as the rate of new arrivals increases. Since the channel capacity wasted due to collisions is less for LWT CSMA than for LBT CSMA, an improvement in throughput results for LWT CSMA.

All CSMA protocols are sensitive to variations in the propagation delay (a). The throughput curves in Figure 3 for non-persistent LWT CSMA and non-persistent LBT CSMA would be superimposed on the throughput curve of pure ALOHA for values of a=.90 and a=.75 respectively. The same curves are superimposed on the throughput curve of slotted ALOHA for values of a=.34 and a=.24 respectively. For example, consider a 1 megabit/second packet radio system transmitting 1000 bit packets. Assume that the assumptions of Section 2.0 are valid. Then the throughput behavior of the non-persistent LBT CSMA and LWT CSMA protocols would be inferior to the throughput behavior of the slotted ALOHA protocol at distances beyond 45 miles and 60 miles respectively. The throughput behavior of pure ALOHA would be superior to that of non-persistent LBT CSMA beyond a distance of 140 miles and superior to that of non-persistent LWT CSMA beyond 170 miles.

5.0 DELAY ANALYSIS

The throughput-delay equation for the non-persistent LWT CSMA protocol is developed in this section using the same arguments expressed in Reference [2] where the delay equations for various LBT protocols were developed.

5.1 Delay Analysis for the Non-Persistent LWT CSMA Protocol

The average delay ($\bar{D}$) for packets on the channel may be represented by the following expression:

$$\bar{D} = \begin{bmatrix} \text{average delay} \\ \text{due to} \\ \text{collisions} \end{bmatrix} + \begin{bmatrix} \text{average delay} \\ \text{due to} \\ \text{deferring} \end{bmatrix} + \begin{bmatrix} \text{delay due} \\ \text{to trans-} \\ \text{mission} \end{bmatrix}$$

or equivalently,

$$\bar{D} = P\,[\text{collision}]\ (\text{duration of collision}) + P\,[\text{deferring}]\ (\text{duration of deferral}) + \text{transmission time.}$$

The delays incurred by an individual packet are:

$(2a + \delta)$ - if a packet collides,*

δ - if a packet is blocked,

$(1+a)$ - the packet transmission time,

where δ is the normalized mean packet retransmission delay.

---

*See figure 1. The first packet of a collision is delayed for a period d, $(2a \leq d \leq 3a)$. Other packets of a collision are delayed for a period d, $(a \leq d \leq 2a)$. The assumption is made that the average delay per packet involved in the collision is $(2a+\delta)$.

All of the traffic which arrives at the channel does not attempt to transmit. Define H to be the proportion of the offered channel traffic which attempts to transmit. The channel traffic that is blocked is (G-H). The mean number of times a packet transmission is attempted before a successful transmission occurs (mean number of collisions) is (H-S)/S. The mean number of times a packet is blocked is (G-H)/S. The average delay for packets on the channel is:

$$\bar{D} = [(H-S)/S](2a+\delta) + [(G-H)/S]\delta + 1 + a \tag{5}$$

H, the proportion of the offered channel traffic which attempts to transmit is determined by using some of the results of the throughput analysis of Section 4.0. Let P_b be the probability that a user having a packet to transmit is blocked, i.e., senses the channel busy and reschedules the packet for retransmission. Then $(1-P_b)$ is the probability the user senses the channel is idle.

$$(1-P_b) = P\begin{bmatrix}\text{arrival occurs within}\\ \text{propagation delay after}\\ \text{start of busy period}\end{bmatrix} + P\begin{bmatrix}\text{arrival occurs}\\ \text{during an idle}\\ \text{period}\end{bmatrix}$$

From renewal theory:

$$(1-P_b) = \frac{a}{\bar{B} + \bar{I}} + \frac{\bar{I}}{\bar{B} + \bar{I}}$$

Using $\bar{B}$ and $\bar{I}$ from Section 3.1:

$$(1-P_b) = \frac{a + 1/G}{(e^{-aG}+a) + (1/G+a)(1-e^{-aG})^2 + 1/G}$$

$$= \frac{aG + 1}{G(e^{-aG}+a) + (1+aG)(1-e^{-aG})^2 + 1}$$

Assume that the probability of a successful transmission is the same each time a user attempts to transmit. The number of times users actually attempt to transmit is:

$$H = G\,(1-P_b).$$

All variables necessary to calculate the average delay for non-persistent LWT CSMA have been defined.

5.2 Delay Comparisons of LWT CSMA vs LBT CSMA and ALOHA Protocols

The corresponding delay equation for non-persistent LBT CSMA is given by [2]:

$$D = [(H-S)/S](1 + 2a + w + \delta) + [(G-H)/S]\delta + 1 + a$$

where w is the normalized acknowledgement transmission time, and each packet must be completely transmitted and negatively acknowledged before retransmission can be attempted. H and P_b are calculated using $\bar{B}$ and $\bar{I}$ from Section 4.2 in the manner described for the LWT case.

The delay equations for other LBT CSMA protocols and ALOHA protocols are developed in Reference[2] .

Figure 4 illustrates the theoretical delays for various contention protocols with a=.05, w=.01, δ=.12. The non-persistent LWT protocol appears to offer a 30 to 100 percent decrease in mean delay performance over non-persistent LBT for equivalent throughput values, and approximately a 10 to 20 percent improvement in maximum throughput.

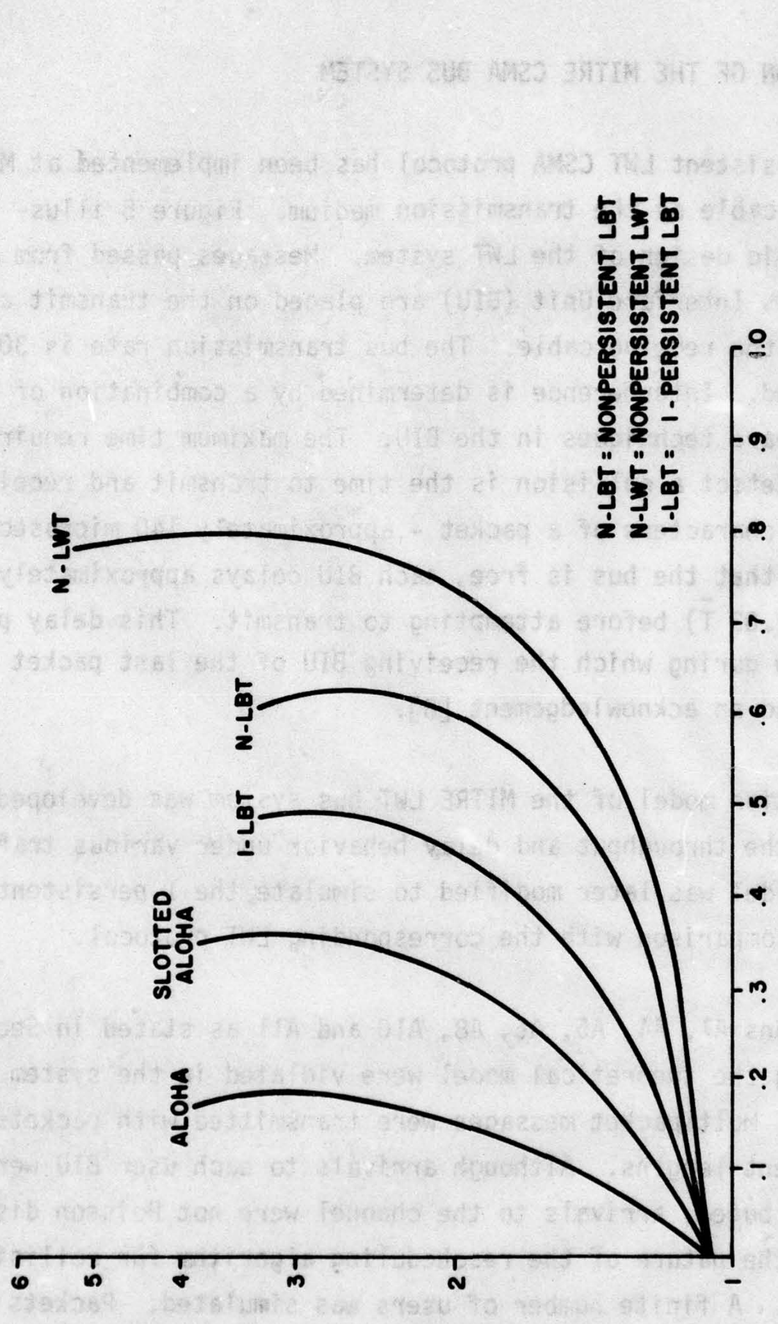

Figure 4 - ANALYTIC DELAY RESULTS ($a = 0.05$, $\bar{\delta} = 0.12$)

IA-53201

6.0 SIMULATION OF THE MITRE CSMA BUS SYSTEM

The 1-persistent LWT CSMA protocol has been implemented at MITRE using coaxial cable as the transmission medium. Figure 5 illustrates the basic design of the LWT system. Messages passed from a device to a Bus Interface Unit (BIU) are placed on the transmit cable and sensed on the receive cable. The bus transmission rate is 307.2 Kilobits/second. Interference is determined by a combination of hardware and software techniques in the BIU. The maximum time required for a BIU to detect a collision is the time to transmit and receive the first two characters of a packet - approximately 140 microseconds. After sensing that the bus is free, each BIU delays approximately 100 microseconds (.03 $\bar{T}$) before attempting to transmit. This delay provides a window during which the receiving BIU of the last packet transmitted may send an acknowledgement [8].

A simulation model of the MITRE LWT bus system was developed to ascertain the throughput and delay behavior under various traffic loads. The model was later modified to simulate the 1-persistent LBT protocol for comparison with the corresponding LWT protocol.

Assumptions A1, A4, A5, A6, A8, A10 and A11 as stated in Section 3.0 concerning the theoretical model were violated in the system implementation. Multipacket messages were transmitted with packets having different lengths. Although arrivals to each user BIU were Poisson distributed, arrivals to the channel were not Poisson distributed due to the nature of the rescheduling algorithm for collisions and deferrals. A finite number of users was simulated. Packets were allowed to queue at each BIU. The propagation delays for users were distributed uniformly in the range 2 to 40 microseconds (.0006 $\bar{T}$ to .012 $\bar{T}$). The time required for a BIU to detect a collision was greater than the propagation delay due to the software collision detection technique mentioned above. Acknowledgement traffic was also transmitted on the channel.

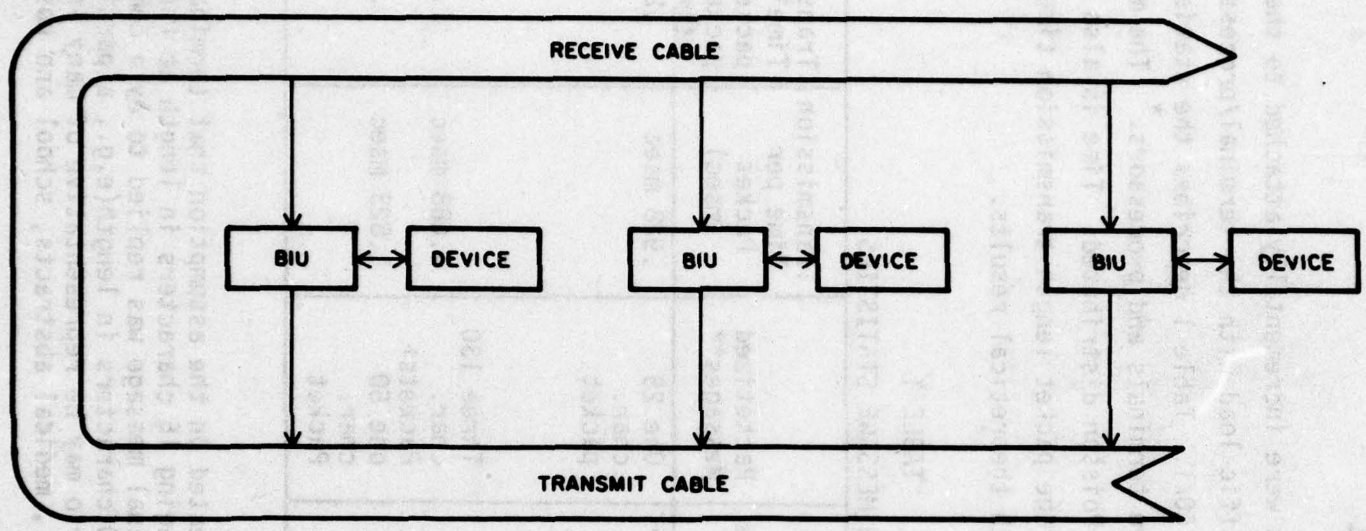

Figure 5 - MITRE LWT BUS ARCHITECTURE

IA-53200

6.1 Message Loading Scenario

Terminals and processors were incrementally attached to the system to present an offered traffic load with the terminal/processor ratio maintained constant at 50/1. Table 1 describes the statistics for messages exchanged between terminals and processors.* The message arrivals from each user were Poisson distributed. Time is also measured in units of the average packet length transmission time, $\bar{T}$, to facilitate comparisons with theoretical results.

TABLE 1

SIMULATION MESSAGE STATISTICS

Direction of Message Flow	Average Message Arrival Rate	Message Length	Packetized Messages**	Transmission Time per Packet (msec)	Transmission Time*** per packet (avg. packet xmit time)
From Terminal to Processor	2/min	15 char.	One 25 char. packet	.928 msec	.27 $\bar{T}$
From Processor to Terminal	2/min	400 char.	Three 130 char. Packets+ one 50 char. Packet	4.688 msec 1.823 msec	1.40 $\bar{T}$ .54 $\bar{T}$

*The message scenario was created on the assumption that terminals were sending short messages averaging 15 characters in length at the rate of 2 per minute. Each terminal message was replied to by a computer with a message averaging 400 characters in length(e.g., a partial CRT screen update). This scenario may be representative of many information retrieval systems, e.g., medical abstracts, school and hospital admissions or registration.

**Includes 10 character packet header.

***$\bar{T}$, average packet transmission time = 3.36 msec.

6.2 Simulation Results for the LWT 1-persistent Protocol

The average throughput and delay obtained for various terminal/ processor configurations using the LWT 1-persistent protocol are listed in Table 2 for two different values of the average retransmission delay.

TABLE 2

LWT CSMA THROUGHPUT AND DELAY VS NUMBER OF USERS AND RETRANSMISSION DELAY

Number of Terminal/ Processor Users	Mean Retransmission Delay $\delta = .12\ \bar{T}$		Mean Retransmission Delay $\delta = .24\ \bar{T}$	
	Avg. Throughput	Av.Delay	Avg. Throughput	Avg.Delay
100/2	.06	1.10 $\bar{T}$	----	----
200/4	.12	1.20 $\bar{T}$	----	----
400/8	.24	1.27 $\bar{T}$	.24	2.1 $\bar{T}$
600/12	.36	1.42 $\bar{T}$	----	----
800/16	.48	1.94 T	----	----
1000/20	.54	2.66 T	----	----
1200/24	.60	3.54 T	----	----
1300/26	0*	∞*	.77	4.3 $\bar{T}$
1400/28	0*	∞*	.83	9.27 $\bar{T}$
1500/1+	.89	1.60 T	----	----
1500/30	0	∞*		

*Unstable channel

+The single processor outputs messages at a rate equivalent to 30 normal processors.

The initial simulation runs were made using a random retransmission delay uniformly distributed in the range 0 $\bar{T}$ to .24 $\bar{T}$ with a mean (δ) of .12 $\bar{T}$. The increase in throughput and delay was nearly linear until the configuration of 1300 terminals and 26 processors, corresponding to a required channel utilization of about .75, was attempted. The channel then became saturated and throughput dropped to zero.

The retransmission delay was changed to a uniform distribution in the range 0 $\bar{T}$ to .48 $\bar{T}$ with a mean of .24 $\bar{T}$. Equilibrium was achieved for the 1300 terminal and 26 processor configuration. This behavior is the same as the LBT CSMA behavior described in References [2-5].* The higher the input load, the larger the average retransmission delay must be to prevent the channel from saturating. However, lengthening the value of the average retransmission delay increases the delay at lower throughput values, as indicated by the delay values for the 400 terminal and 8 processor configuration.

The sensitivity of the network saturation point to the number of users is indicated by the results using a 1500 terminal and single processor configuration. The single processor was generating messages at a rate equivalent to 30 normal processors. The channel did not become saturated for the configuration using the single processor. The channel was rapidly saturated when the single processor was replaced by 30 processors generating a traffic load equivalent to that of the single processor. This behavior is consistent with the

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*This behavior disagrees with the conjecture made in Reference 8 that throughput does not decrease as G increases. Throughput did not decrease for that case due to the small number of users simulated.

behavior of other contention systems, i.e., as the number of channel users is increased, an originally stable channel becomes unstable although the channel input rate remains constant [2].

6.3 Simulation Results for the 1-persistent LBT CSMA Protocol

The 1-persistent LBT CSMA protocol was simulated as it would be implemented on the MITRE cable system. The average throughput and delay obtained for various terminal/processor configurations are listed in Table 3 for various values of average retransmission delay. The values in Table 3 should be compared with the values listed in Table 2 for the 1-persistent LWT protocol.

TABLE 3

LBT CSMA THROUGHPUT AND DELAY VS NUMBER OF USERS AND RETRANSMISSION DELAY

Number of Terminal/ Processor Users	Average Throughput	Average Delay	Mean Retransmission Delay δ
100/2	---	---	---
200/4	.12	2.48 $\bar{T}$	.12 $\bar{T}$
400/8	.24	3.53 $\bar{T}$	7.6 $\bar{T}$
600/12	.36	5.70 $\bar{T}$	7.6 $\bar{T}$
700/14	.42	11.38 $\bar{T}$	15.2 $\bar{T}$
800/16	0	∞	15.2 $\bar{T}$

The behavior of the LBT protocol is similar to that of the corresponding LWT protocol. The throughput increased until the channel became saturated when the 400 terminal/8 processor configuration was simulated with a retransmission delay uniformly distributed in the range 0 $\bar{T}$ to .24 $\bar{T}$. Increasing the retransmission delay to range between 0 $\bar{T}$ and 15.2 $\bar{T}$ enabled the channel to achieve equilibrium conditions. The channel again reached saturation for the 700 terminal/14 processor configuration. Increasing the retransmission delay to range between 0 $\bar{T}$ and 30.4 $\bar{T}$ resulted in the establishment of equilibrium conditions. The channel became saturated again when the 800 terminals and 16 processor configuration was attempted.

6.4 Comparison of 1-persistent LWT and LBT CSMA Simulation Results

The performance of the 1-persistent LWT protocol is superior to that of the corresponding LBT protocol. The maximum throughput achieved by the LBT protocol is less than half the maximum throughput achieved by the LWT protocol. The delays incurred by the LBT protocol are more than twice the value of the delays incurred by the LWT protocol at the same throughput rate. The LBT protocol requires a much larger mean retransmission delay to prevent channel saturation than does the LWT protocol at equivalent input traffic rates. Figures 6 and 7 illustrate the throughput vs offered channel traffic and the delay vs throughput simulation results for the 1-persistent LWT and LBT CSMA protocols.

The dynamic behavior of the channel was the same for both protocols. The channel was saturated after some finite time period of quasi-stationary conditions. Channel equilibrium was achieved by increasing the mean retransmission delay. Decreasing the number of users while maintaining the same input traffic rate, may also stabilize the channel. Therefore, the theoretical equilibrium throughput-delay results do not completely describe the performance of a contention

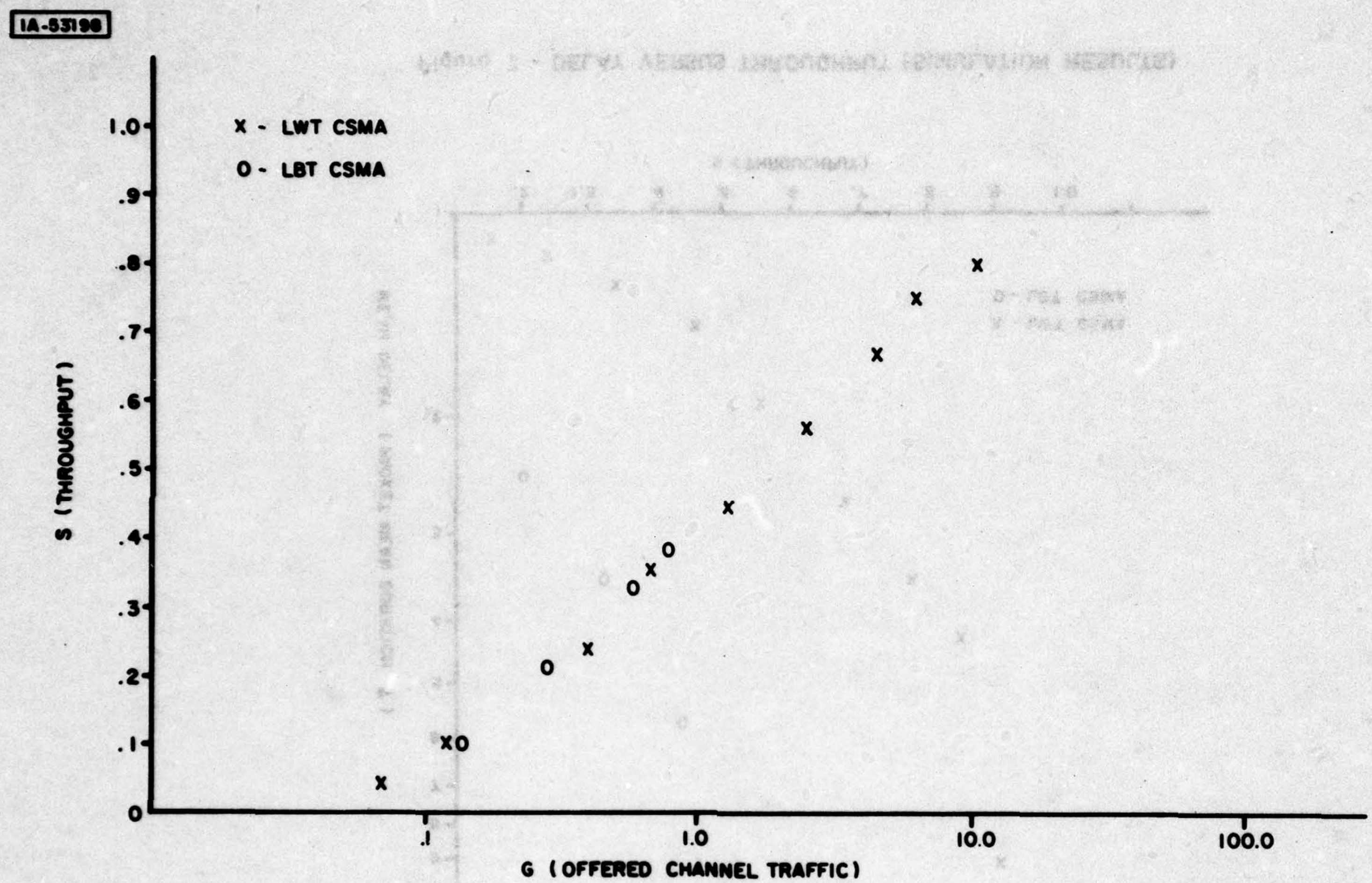

Figure 6 - THROUGHPUT VERSUS OFFERED CHANNEL TRAFFIC
(SIMULATION RESULTS)

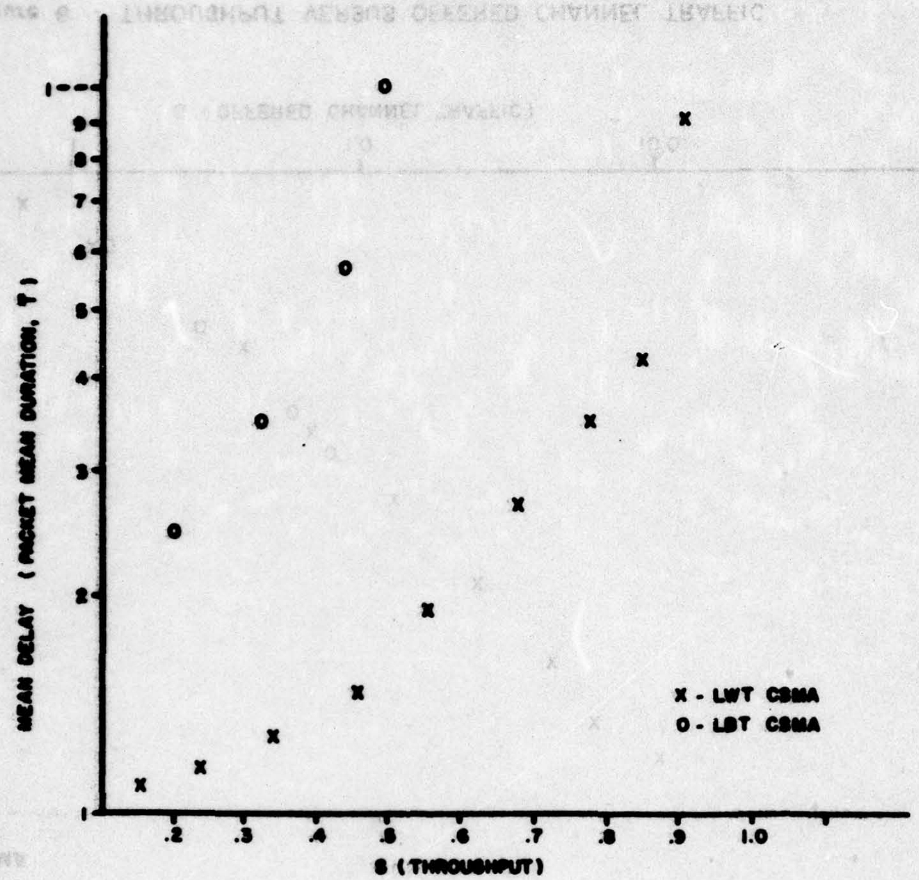

Figure 7 - DELAY VERSUS THROUGHPUT (SIMULATION RESULTS)

channel for a large number of users. The channel performance is better represented by use of a stability throughput-delay trade-off. Reference [5] describes the stability throughput-delay trade-off for a Slotted ALOHA channel. F. Tobagi and L. Kleinrock have described the throughput-stability trade-offs for the non-persistent LBT CSMA protocol [1, 3].

The solutions for preventing channel saturation are the same for the LWT CSMA, LBT CSMA [4] and ALOHA [5] protocols. They are control the input traffic rate, increase the retransmission delay or decrease the number of users. The dynamic control procedures investigated for the LBT CSMA and ALOHA protocols are applicable to the LWT CSMA protocol.

7.0 CONCLUSIONS

Equilibrium throughput and delay equations have been derived for the non-persistent LWT CSMA and LBT CSMA channel transmission protocols. The non-persistent LWT CSMA protocol offers theoretical improvements of 10 to 20 percent increase in maximum throughput and 30 to 100 percent decrease in delay when compared to the non-persistent LBT CSMA protocol.

The performance of the 1-persistent LWT CSMA and LBT CSMA protocols, as implemented on the MITRE uni-directional coaxial cable system, was investigated using computer simulation. The maximum throughput achieved by the LWT protocol was twice as great as the maximum throughput achieved by the LBT protocol. The LWT protocol exhibited a 100 to 800 percent decrease in packet delay when compared to the LBT protocol at the same throughput rate.

The LWT CSMA protocol behaves in a manner consistent with the behavior for the LBT CSMA protocol as described by F. Tobagi [2]. For a specified mean retransmission delay the channel becomes saturated with retransmissions as the input traffic rate increases. Increasing the mean retransmission delay enables the channel to achieve equilibrium conditions. Decreasing the number of users, while maintaining the same input traffic rate, may also stabilize the channel. The stability considerations and dynamic control procedures described by Lam, Kleinrock and Tobagi [1-4] for LBT CSMA and ALOHA protocols are applicable to LWT CSMA protocols.

REFERENCES

1. N. Abramson, "The Theory of Packet Broadcasting", TRB76-1, The ALOHA System, University of Hawaii, January 1976.

2. F. Tobagi, "Random Access Techniques for Data Transmission Over Packet Switched Radio Networks", Computer Sci Dept. School Eng. Appl. Sci., University of California, Los Angeles, UCLA-ENG 7499 December 1974.

3. L. Kleinrock and F. Tobagi, "Packet Switching in Radio Channels: Part I - Carrier Sense Multiple Access Modes and Their Throughput Delay Characteristics", IEEE Trans. Commun., Vol. COM-23, No. 12, December 1975.

4. F. Tobagi and L. Kleinrock, "Packet Switching in Radio Channels: Part IV - Stability Considerations and Dynamic Control in Carrier Sense Multiple Access", IEEE Trans. Commun., Vol. COM-25, No. 10, October 1977.

5. S. Lam and L. Kleinrock, "Packet Switching in a Multiaccess Broadcast Channel: Dynamic Control Procedures", IEEE Trans. Commun., Vol. COM-23, No. 9, September 1975.

6. M. Ferguson, "A Study of Unslotted ALOHA with Arbitrary Message Lengths", The ALOHA System Tech. Report B75-13, February 1975.

7. D. Cox, Renewal Theory, Methuen (London) 1962.

8. A. Agrawala, R. Bryant, J. Agre, "Analysis of an ETHERNET-Like Protocol", Proc. of Comp. Networking Symposium, Gaithersburg, MD., December 1977.